

A large sample of low surface brightness disc galaxies from the SDSS- II. Metallicities in surface brightness bins

Y. C. Liang^{1,2*}, G. H. Zhong^{1,2,3}, F. Hammer⁴, X. Y. Chen^{1,2,3}, F. S. Liu^{5,1,2},
D. Gao^{1,2,3}, J. Y. Hu^{1,2}, L. C. Deng^{1,2}, B. Zhang^{6,1,2}

¹National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, China

²Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

³Graduate School of the Chinese Academy of Sciences, Beijing 100049, China

⁴GEPI, Observatoire de Paris-Meudon, 92195 Meudon, France

⁵College of Physics Science and Technology, Shenyang Normal University, Shenyang 110034, China

⁶Department of Physicals, Hebei Normal University, Shijiazhuang 050016, China

Accepted . Received

ABSTRACT

We study the spectroscopic properties of a large sample of Low Surface Brightness galaxies (LSBGs) (with B-band central surface brightness $\mu_0(B) > 22$ mag arcsec⁻²) selected from the Sloan Digital Sky Survey Data Release 4 (SDSS-DR4) main galaxy sample. A large sample of disk-dominated High Surface Brightness galaxies (HSBGs, with $\mu_0(B) < 22$ mag arcsec⁻²) are also selected for comparison simultaneously. To study them in more details, these sample galaxies are further divided into four sub-groups according to $\mu_0(B)$ (in units of mag arcsec⁻²): vLSBGs (24.5–22.75), iLSBGs (22.75–22.0), iHSBGs (22.0–21.25), and vHSBGs (<21.25). The diagnostic diagram from spectral emission-line ratios shows that the AGN fractions of all the four sub-groups are small (<9%). The 21,032 star-forming galaxies with good quality spectroscopic observations are further selected for studying their dust extinction, strong-line ratios, metallicities and stellar mass-metallicities relations. The vLSBGs have lower extinction values and have less metal-rich and massive galaxies than the other sub-groups. The oxygen abundances of our LSBGs are not as low as those of the H II regions in LSBGs studied in literature, which could be because our samples are more luminous, and because of the different metallicity calibrations used. We find a correlation between $12 + \log(\text{O}/\text{H})$ and $\mu_0(B)$ for vLSBGs, iLSBGs and iHSBGs but show that this could be a result of correlation between $\mu_0(B)$ and stellar mass and the well-known mass-metallicity relation. This large sample shows that LSBGs span a wide range in metallicity and stellar mass, and they lie nearly on the stellar mass vs. metallicity and N/O vs. O/H relations of normal galaxies. This suggests that LSBGs and HSBGs have not had dramatically different star formation and chemical enrichment histories.

Key words: galaxies: abundances - galaxies: evolution - galaxies: ISM - galaxies: spiral - galaxies: starburst - galaxies: stellar content

1 INTRODUCTION

Low Surface Brightness Galaxies (LSBGs) are important populations in the field environments. However, their properties were seldom studied and their contributions to the galaxy population were underestimated since they are hard to find owing to their faintness compared with the night sky. An initial quantitative study was done by Freeman (1970),

who noticed that the central surface brightness of their 28 out of 36 disc galaxies fell within a rather narrow range, $\mu_0(B) = 21.65 \pm 0.3$ mag arcsec⁻². This could be caused by selection effects as pointed out by Disney (1976), and had been previously recognized by Zwicky (1957).

Since then, many efforts were made to search for LSBGs from surveys, and a sample of LSBGs were gathered after then. Specially, Impey and his colleagues adopted the Automated Plate Measuring (APM) mechanism to scan UK Schmidt plates and discovered 693 LSB field galaxies which

* E-mail: ycliang@nao.cas.cn

forms the most extensive catalog of LSBGs to that date (Impey et al. 1996). Then, their group studied the properties of this sample of LSBGs in a series of works. O’Neil et al. (1997a,b in “Texas survey”) firstly found the red LSB galaxy populations. Monnier Ragaigine et al. (2003a,b,c) selected a sample of about 3800 LSBGs from the all-sky near-infrared 2MASS survey, and then obtained the 21 cm H I observations and estimated the H I masses for two subsamples of 367 and 334 LSBGs. More related references about LSBG searching and catalogs could be found in Bothun, Impey, McGaugh (1997), Impey & Bothun (1997) and Zhong et al. (2008).

The modern Sloan digital sky survey (SDSS, York et al. 2000) has its great advantages to extend the sample of LSBGs and study their physical properties in details. It provides to the public the homogeneous data of photometric and spectroscopic observations for several hundred thousands galaxies. Therefore, it will be very powerful and appropriate to search for a large sample of LSBGs from the SDSS.

Kniazev et al. (2004) developed a method to search for LSBGs from the SDSS early data release (EDR, Stoughton et al. 2002) field images and used the sample of Impey et al. (1996) to test their method. They recovered 87 same objects as in Impey et al. and 42 new LSBGs. Bergvall et al. (2009) studied the red halos of 1510 nearly edge-on LSBGs from SDSS. Mattsson et al. (2008) discussed the N, O abundances of a subsample of them. Rosenbaum & Bomans (2004) studied the large-scale environment of LSBGs based on SDSS-EDR data, and Rosenbaum et al. (2009) extend the sample to Data Release 4 (DR4, Adelman-McCarthy et al. 2006) to get more detailed results. Our group has successfully selected a large sample of nearly face-on disc LSBGs from SDSS-DR4 main galaxy sample (Strauss et al. 2002). In Zhong et al. (2008), we present their basic photometric properties including the clear correlations of disk scalelength versus B-band absolute magnitude and distance (also see the similar results of Graham & Worley 2008 for high surface brightness galaxies, HSBGs), and the stellar populations from colors. This large sample includes 12,282 LSBGs with $\mu_0(B) < 22$ mag arcsec $^{-2}$, and another 18,051 HSBGs with $\mu_0(B) > 22$ mag arcsec $^{-2}$ are also selected for comparisons.

Chemical abundance is an fundamental property of galaxy. The chemical properties of stars and gas within a galaxy provide both a fossil record of its star formation history and information on its present evolutionary status. Some researchers have obtained the metallicities of some H II regions in a small sample of LSBGs. For example, McGaugh (1994) obtained the oxygen abundances of 41 H II regions in 22 LSBGs, Roennback & Bergvall (1995) obtained oxygen abundances for 24 H II regions in 16 blue LSBGs. de Blok & van der Hulst (1998) present measurements of the oxygen abundances of 64 H II regions in 12 LSBGs, Kuzio de Naray et al. (2004) reported the oxygen abundances of 16 H II regions in 6 LSBGs. Their results show that these H II regions in the sample of LSBGs have low metallicities, the $12+\log(O/H)$ is about 8.06 to 8.20 (in median in the samples), which could mean that the LSBGs are metal-poor and unevolved systems.

In this second paper of our series work about the large sample of nearly face-on LSBGs selected from the SDSS-

DR4 main galaxy sample (Zhong et al. 2008, Paper I), we will study their spectroscopic properties, in particular, quantities that can be derived from nebular emission line ratios. We will measure nuclear activity, dust extinction, oxygen abundances, nitrogen to oxygen ratios, and examine the stellar mass-metallicity relations, the relations of metallicities vs. $\mu_0(B)$ and stellar masses vs. $\mu_0(B)$. The same property parameters are also obtained for the HSBGs for comparisons. To be in more details, the LSBGs and HSBGs are taken as a whole sample to be divided into four subgroups according to $\mu_0(B)$ for the studies mentioned above.

This paper is organized as follows. In Sect.2, the sample selection criteria are given and the Active Galactic Nucleus (AGN) fractions are estimated from BPT (Baldwin, Phillips, Terlevich 1981) diagram. In Sect.3, we present the dust extinction, diagnostic diagram of emission-line ratios, oxygen abundances and $\log(N/O)$ abundance ratios of the sample galaxies. In Sect.4, we present the stellar mass-metallicity relations, and the relations of $12+\log(O/H)$ vs. $\mu_0(B)$, and stellar mass $\log M_*$ vs. $\mu_0(B)$ for the sample galaxies. The discussions are given in Sect. 5. In Sect. 6, we summarize and conclude the work. Throughout this paper, a cosmological model with $H_0=70$ km s $^{-1}$ Mpc $^{-1}$, $\Omega_M=0.3$ and $\Omega_\Lambda = 0.7$ has been adopted.

2 THE SAMPLE

The parent sample of this work is the 30,333 nearly face-on disc galaxies selected from SDSS-DR4 main galaxy sample by Zhong et al. (2008). Here we match this sample with the emission line catalog of SDSS-DR4 to get a subsample of star-forming galaxies to study their spectral properties, especially metallicities. The fluxes of the emission-lines of the sample galaxies are taken from publication of the MPA/JHU collaboration (the MPA SDSS website¹, Kauffmann et al. 2003a,b; Brinchmann et al. 2004; Tremonti et al. 2004 etc.). These measurements were obtained from the stellar-feature subtracted spectra with the spectral population synthesis code of Bruzual & Charlot (2003). The sample selection criteria of this work are given as follows. To be clear, the selection criteria in Zhong et al. (2008) are also simply mentioned.

- (i) $fracDev_r < 0.25$

The parameter $fracDev_r$ indicates the fraction of luminosity contributed by the de Vaucouleurs profile relative to exponential profile in the r -band. This means the selected sample almost having an exponential light profile rather than a de Vaucouleurs profile. This can also minimize the effect of bulge light on the disk galaxies.

- (ii) $b/a > 0.75$

This is for selecting the nearly face-on disc galaxies, and this is corresponding to the inclination $i < 41.41$ degree, where a and b are the semi-major and semi-minor axes of the fitted exponential disk, respectively.

- (iii) $M_B < -18$

This B-band absolute magnitude cut excludes the few dwarf galaxies ($\sim 6\%$) contained in the sample by the previous two steps of selection.

¹ <http://www.mpa-garching.mpg.de/SDSS/>

Up to now, 30,333 nearly face-on disc galaxies are selected. Taking $\mu_0(B)=22$ mag arcsec $^{-2}$ as the criterion, 12,282 objects are classified as LSBGs and other 18,051 objects as HSBGs. More details can be found in Zhong et al. (2008).

(iv) $0.04 < z < 0.25$

This redshift range may ensure a covering fraction $>20\%$ of the galaxy light in the SDSS spectral observations, and allow us to get reliable metallicity estimates for the galaxies (Kewley et al. 2005; Liang et al. 2006a). Then 28,148 (92.8% of 30,333) of our sample galaxies are within this redshift range, which includes 11,086 (90.3% of 12,282) LSBGs and 17,062 (94.5% of 18,051) HSBGs. The aperture effects will be specially discussed in Sect. 5.

(v) Emission line selection

We require the fluxes of the emission lines have been measured for [O II]3727, H β , [O III]5007, H α , [N II]6583, [S II]6717,6731, and they should have higher S/N ratios by requiring the lines of H β , H α , and [N II]6583 detected at greater than 5σ (following Tremonti et al. 2004 and Liang et al. 2006a). Then, it results in 22,757 (81% of 28,148) nearly face-on disc galaxies, which include 7,419 (67% of 11,086) LSBGs and 15,338 (90% of 17,062) HSBGs. We have checked the effects of the S/N ratios of these three emission lines for the sample selection. If only H α is detected at greater than 5σ , the obtained LSBGs and HSBGs are 8,005 and 15,527, respectively; if only [N II]6583 has S/N $> 5\sigma$, the corresponding numbers are 7,916 and 15,540; and if only H β has S/N $> 5\sigma$, the corresponding numbers are 7,538 and 15,383. This means that H β plays larger role than H α and [N II] in limiting the sample. The effect of [O III]5007 will be further discussed in the later part of this section, and the effect of emission line selection for LSBGs will be further discussed in Sect. 5.

(vi) Four subgroups according to $\mu_0(B)$

By following McGaugh (1996) and the discussion in Zhong et al. (2008), we try to further divide our total sample of nearly face-on disc galaxies (22,757) into four subgroups according to their B-band central surface brightness $\mu_0(B)$ (the method for calculating $\mu_0(B)$ can be found in Sect. 2.2 of Zhong et al. 2008). We divide LSBGs into “vLSBGs” (very Low Surface Brightness Galaxies) and “iLSBGs” (intermediate Low Surface Brightness Galaxies), HSBGs into “iHSBGs” (intermediate High Surface Brightness Galaxies) and “vHSBGs” (very High Surface Brightness Galaxies). These acronyms differ slightly from those adopted by McGaugh et al. (1996). The numbers of galaxies in the four subgroups are:

1,364 (18% of 7,419) vLSBGs with $22.75 < \mu_0(B) < 24.5$ mag arcsec $^{-2}$,

6,055 (82% of 7,419) iLSBGs with $22 < \mu_0(B) < 22.75$ mag arcsec $^{-2}$,

9,107 (59% of 15,338) iHSBGs with $21.25 < \mu_0(B) < 22$ mag arcsec $^{-2}$, and

6,231 (41% of 15,338) vHSBGs with $\mu_0(B) < 21.25$ mag arcsec $^{-2}$.

Indeed, McGaugh (1996) named these four subgroups of $\mu_0(B)$ bins as LSBGs, ISBGs, HSBGs and VHSBGs consequently.

(vii) Star-forming galaxies

For metallicity estimates of galaxies, only star-forming galaxies are selected. The traditional line diagnostic diagram [N II]/H α vs. [O III]/H β (BPT: Baldwin, Phillips, Ter-

levich 1981; Veilleux & Osterbrock 1987) is used to separate the star-forming galaxies from AGNs. We adopt the formula given by Kauffmann et al. (2003a, the solid line in Fig. 1): $\log([\text{O III}]/5007/\text{H}\beta) < 0.61/(\log([\text{N II}]/6583/\text{H}\alpha) - 0.05) + 1.3$, to select the star-forming galaxies. Kewley et al. (2001) also gave a diagnostic line, which often is assumed as the upper limit for star-forming galaxies (see the dashed line in Fig. 1).

Finally we select 21,032 (92.4%) star-forming galaxies from the 22,757 galaxies having good quality spectral observations. In each of the four subgroups of surface brightness, there are 1,299 (95.2% of 1,324) vLSBGs, 5,551 (91.7% of 6,055) iLSBGs, 8,310 (91.2% of 9,107) iHSBGs, and 5,872 (94.2% of 6,231) vHSBGs. These mean that the AGN fractions of these sample galaxies are quite small, less than 9%, and vLSBGs has the least fraction of AGNs, $<5\%$. Fig. 1 presents these results. The AGN fraction here is much lower than that (33%) found by Tremonti et al. (2004) for the whole sample of star-forming galaxies. The reason could be that our *fracDev_r* cut has selected against galaxies with bulges, and we only select the nearly face-on disc galaxies. The bulge mass is very tightly correlated with black hole mass (Kormendy & Richstone 1995; Magorrian et al. 1998).

The median values of the B band central surface brightnesses $\mu_0(B)$ (in units of mag arcsec $^{-2}$) in the four subgroups are: 22.96 for vLSBGs, 22.28 for iLSBGs, 21.64 for iHSBGs, and 20.86 for vHSBGs. The corresponding mean values of them are 23.02, 22.31, 21.64 and 20.77, respectively. We will study these star-forming galaxies in the following parts of this work.

The MPA/JHU group has provided the $12+\log(\text{O}/\text{H})$ abundances for the SDSS star-forming galaxies as given in Tremonti et al. (2004). For our sample galaxies, we will adopt the oxygen abundances measured by them. The reason will be discussed in Sect. 3.2 in details. Due to the number limits of the sample with reliable oxygen abundance measurements, the numbers of our sample galaxies in each of the four subgroups are then reduced to 601 (46% of 1,299) of vLSBGs, 2,630 (47% of 5,551) of iLSBGs, 5,517 (66% of 8,310) of iHSBGs, and 5,317 (90% of 5,872) of vHSBGs.

The reason for the large fraction of reduced numbers here could be mainly due to the S/N cut of [O III]5007 $> 5\sigma$, which probably was used in producing the MPA/JHU metallicity catalog, although was not used by Tremonti et al. (2004). We have tried to check this guess. In criterion (v), when we only consider [O III]5007 $> 5\sigma$ as the limiting for selecting the sample from S/N ratio, we will obtain 3,440 LSBGs and 11,463 HSBGs, which are much smaller than only considering other three emission lines. Furthermore, if we consider all the four strong emission lines H β , H α , [N II]6583 and [O III]5007 detected at greater than 5σ , the resulted sample will be 3,332 LSBGs and 11,386 HSBGs, which are similar to what obtained by only considering [O III]5007 $> 5\sigma$ as given above. This means, indeed, [O III]5007 plays largest role in limiting the sample. These samples (3,332 and 11,386) are further classified as 3,014 (90.4%) star-forming LSBGs and 10,439 (91.6%) star-forming HSBGs, which still suggest the small AGN fraction ($<10\%$) of the sample galaxies. Then, we divided these star-forming galaxies into four subgroups following their surface brightness. There are 567 vLSBGs, 2,447 iLSBGs, 5,181 iHSBGs and 5,258 vHSBGs.

Table 1. Basic information of the sample galaxies in the four subgroups with $\mu_0(B)$. All the estimates of parameters are in median.

	vLSBG	iLSBG	iHSBG	vHSBG
$\mu_0(B)$	24.5-22.75	22.75-22.0	22.0-21.25	<21.25
All galaxies	1,364	6,055	9,107	6,231
Star forming	1,299	5,551	8,310	5,872
AGN fraction	4.8%	8.3%	8.8%	5.8%
A_V	0.46	0.63	0.76	0.83
with O/H				
Star forming	601	2,630	5,517	5,317
$12+\log(\text{O}/\text{H})$	8.77	8.94	9.03	9.06
$\log(\text{N}/\text{O})$	-1.05	-0.94	-0.85	-0.83
with stellar mass				
Star forming	597	2,609	5,486	5,291
$\log(M_*)$	9.55	9.91	10.21	10.29
light_fraction	0.12	0.15	0.21	0.30

Note : Row (1)-(5) consequently refer to the ranges of $\mu_0(B)$ in units of mag arcsec^{-2} , the numbers of all the sample galaxies; the numbers of star-forming galaxies; AGN fractions and median values of dust extinction. Row (7)-(9) refer to the numbers of the galaxies having oxygen abundance estimates, the median values of oxygen abundances and $\log(\text{N}/\text{O})$ consequently. Row (11)-(13) refer to the numbers of the galaxies having both oxygen abundance and stellar mass estimates, median values of stellar masses and light fractions in the fiber observations consequently.

These four values are quite similar to the numbers of 601, 2,630, 5,517 and 5,317 given in last paragraph, which are obtained by matching the samples from criteria (i)-(vii) with the metallicity catalog of MPA/JHU, although very slight differences still exist.

The stellar masses of the sample galaxies are taken from the MPA/JHU database as well (Kauffmann et al. 2003b, Gallazzi et al. 2005). To estimate stellar masses of the galaxies, they firstly estimated the dust-correction to the observed z -band magnitude of the galaxy, and then the stellar mass was computed by multiplying the dust-corrected luminosity of the galaxy by the stellar mass-to-light ratio predicted by model. In their work, the M/L ratios are estimated by also considering the spectral features. But nearly all other methods use colors to estimate M/L . Due to the limits of reliable stellar mass estimates, our sample galaxies having both metallicities and stellar masses are then reduced to 597 of vLSBGs, 2,609 of iLSBGs, 5,486 of iHSBGs, and 5,291 of vHSBGs.

All the corresponding numbers of sample galaxies and their median values of the property parameters are presented in Table 1.

3 DUST EXTINCTION AND NEBULAR ABUNDANCES

We study the dust extinction, strong emission-line ratios, $12+\log(\text{O}/\text{H})$ abundances and $\log(\text{N}/\text{O})$ abundance ratios of our star-forming sample galaxies in four bins of $\mu_0(B)$ in this section.

3.1 Dust extinction

The dust extinction inside the star-forming galaxies are derived using the Balmer line ratio $H\alpha/H\beta$: assuming case

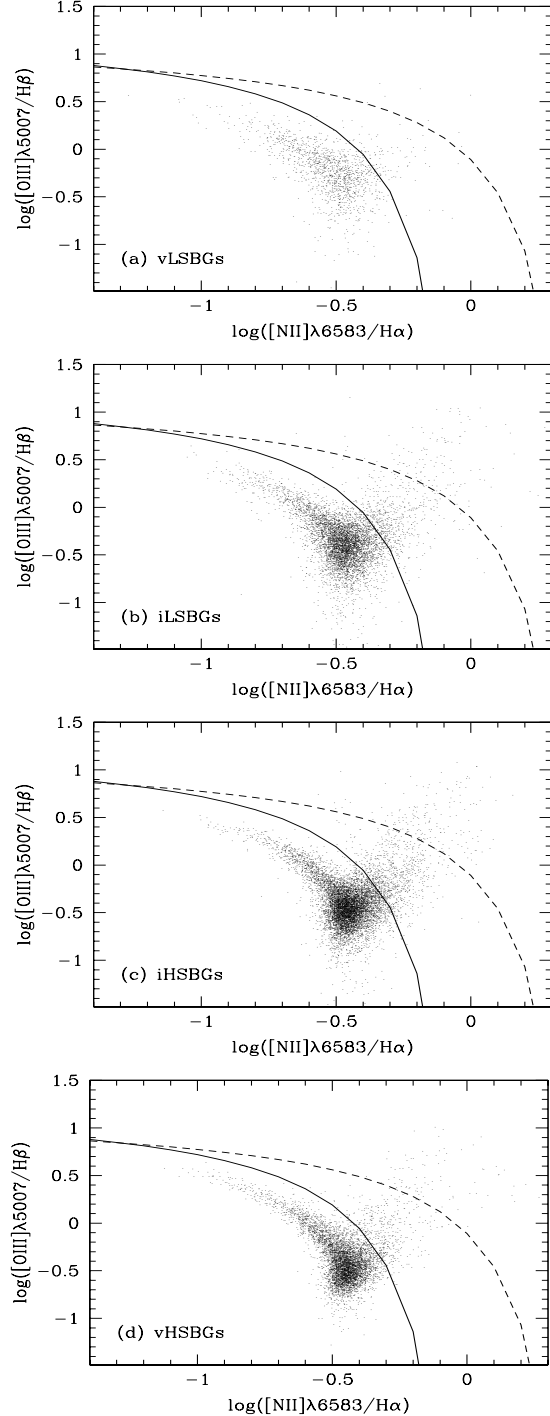


Figure 1. The diagnostic diagrams for star-forming galaxies and AGNs for the sample galaxies in four bins of surface brightness $\mu_0(B)$: (a) vLSBGs, (b) iLSBGs, (c) iHSBGs, (d) vHSBGs. The diagnostic lines come from Kauffmann et al. (2003a, the solid line) and Kewley et al. (2001, the dashed line). The galaxies classified as AGNs fall to the upper right of the lines, and the star-formings fall to the lower left of the lines. We adopt the solid line as the diagnostic line in this work.

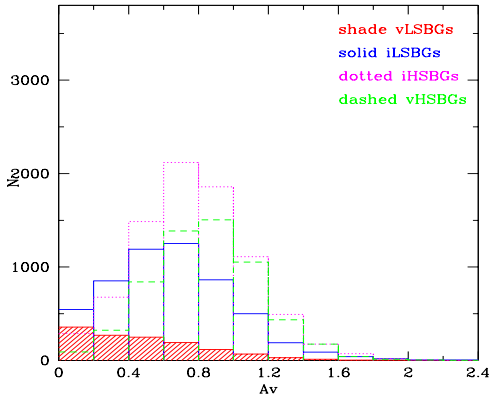


Figure 2. Histogram distributions of dust extinction A_V of the star-forming sample galaxies in four bins of $\mu_0(B)$, the median values are: 0.46 for vLSBGs, 0.63 for iLSBGs, 0.76 for iHSBGs, 0.83 for vHSBGs.

B recombination, with a density of 100 cm^{-3} and a temperature of 10^4 K , and then the predicted intrinsic ratio of $H\alpha/H\beta$ is 2.86 (Osterbrock 1989), with the relation of $(\frac{I_{H\alpha}}{I_{H\beta}})_{\text{obs}} = (\frac{I_{H\alpha}}{I_{H\beta}})_{\text{intr}} 10^{-c(f(H\alpha)-f(H\beta))}$. Using the average interstellar extinction law given by Osterbrock (1989), we have $f(H\alpha) - f(H\beta) = -0.37$. Then, the extinction parameter A_V are calculated following Seaton (1979): $A_V = E(B - V)R = \frac{cR}{1.47}$ (mag). $R = 3.1$ is the ratio of the total to the selective extinction at V . The emission-line fluxes of the sample galaxies have been corrected for this extinction.

The histogram of A_V of the star-forming sample galaxies with bins of 0.2 is given in Fig. 2. The median values of A_V (in units of mag) in the four subgroups are 0.46, 0.63, 0.76 and 0.83 for vLSBGs, iLSBGs, iHSBGs and vHSBGs, respectively (see Table 1). The mean values of A_V are 0.47, 0.65, 0.77 and 0.84, respectively. It shows that the vLSBGs have lower dust extinction than other three subgroups, and it is about 0.2, 0.3, 0.4 mag lower than those of the iLSBGs, iHSBGs and vHSBGs, respectively. If $[O \text{ III}]\lambda 5007 > 5\sigma$ is further considered in criterion (v) in Sect. 2, the selected galaxies will have median values of A_V as 0.36, 0.54, 0.70 and 0.82 for vLSBGs, iLSBGs, iHSBGs and vHSBGs, respectively. Similar to the values above.

3.2 Oxygen abundances

$R_{23} ([O \text{ II}]\lambda 3727 + [O \text{ III}]\lambda 4959, 5007/H\beta)$ is an indicator of metallicity of galaxy. However, one defect of R_{23} is that it results in double-valued $12+\log(O/H)$ abundances, which are for the metal-rich (upper) and metal-poor (lower) branches, respectively, with the transition around $12+\log(O/H) \sim 8.4$ ($\log R_{23} \sim 0.8$). The reason is that, at metal-poor environments, the forbidden lines scale roughly with the chemical abundances, while at metal-rich environments, the nebular cooling is dominated by the infrared fine-structure lines and the electron temperature becomes too low to collisionally excite the optical forbidden lines.

Some other strong-line ratios can break this degeneracy and could also trace the metallicities of the galaxies, such as $[N \text{ II}]\lambda 6583/H\alpha$, $[O \text{ III}]\lambda 5007/[N \text{ II}]\lambda 6583$, $[N \text{ II}]\lambda 6583/[O \text{ II}]\lambda 3727$, $[N \text{ II}]\lambda 6583/[S \text{ II}]\lambda \lambda 6717, 6731$,

$[S \text{ II}]\lambda \lambda 6717, 6731/H\alpha$, and $[O \text{ III}]\lambda \lambda 4959, 5007/H\beta$. Liang et al. (2006a, also Nagao et al. 2006) and Kewley & Dopita (2002) study these line ratios as metallicity indicators from a large sample of SDSS galaxies and photoionization models, respectively. Among these line ratios, $[N \text{ II}]\lambda 6583/[O \text{ II}]\lambda 3727$ was confirmed as the best metallicity calibration because it shows a monotonical increasing following the increasing metallicity and less scatter than other line ratios due to its independence on ionization parameter. However, dust extinction must be estimated properly before using this indicator because the blue line $[O \text{ II}]$ is affected much by dust extinction and is far from $[N \text{ II}]$ in wavelength. Kewley & Ellison (2008) also use $[N \text{ II}]/[O \text{ II}]$ to break the R_{23} degeneracy for their SDSS sample. Their Fig. 8 shows that the division between the R_{23} upper and lower branches occurs at $\log([N \text{ II}]/[O \text{ II}]) \sim -1.2$. But McGaugh (1994) adopted $\log([N \text{ II}]/[O \text{ II}]) \sim -1.0$ as the transition limit.

We present our sample galaxies in the plot of $\log([N \text{ II}]/[O \text{ II}])$ vs. $\log(R_{23})$ in Fig. 3. It shows that most of our sample galaxies have $\log([N \text{ II}]/[O \text{ II}]) > -1.2$, meaning that they should belong to the upper branch of metallicity. This could hint that our sample galaxies are not that metal-poor as the H II regions in the small samples of LSBGs studied by McGaugh (1994) (their Fig. 3), Roennback & Bergvall (1995), de Blok & van der Hulst (1998) and Kuzio de Naray et al. (2004) etc. They found the $12+\log(O/H)$ of those H II regions in LSBGs are 8.06 to 8.20 (the median values of their samples). More discussions will be given in Sect. 5.2.

The strong-line ratios R_{23} can be used to estimate the oxygen abundances of the galaxies. The formula of Tremonti et al. (2004, their Eq.(1)) is used here, which is appropriate for upper branch of metallicity, since Fig. 3 has shown that most of our sample galaxies belong to the upper-branch. However, in this study, for the oxygen abundances of our sample galaxies we prefer to use the values provided by the MPA/JHU group as Tremonti et al. (2004), rather than the R_{23} -based ones. We have checked and found that for the galaxies having relative low metallicities, such as those with $12+\log(O/H)(T04) < 8.6$, the R_{23} method will overestimate their abundances by about 0.1-0.3 dex. This is more obvious for vLSBGs and iLSBGs, and less obvious for iHSBGs and vHSBGs. The reason could be that R_{23} is not a good metallicity indicator for galaxies in the “turn around region” ($\log(R_{23}) > 0.7$; $12+\log(O/H) = 8.2 - 8.6$). First there is the issue of having to decide which branch to use. Second the relation between R_{23} and metallicity becomes very steep in this region, hence small errors in R_{23} will result in large errors in O/H . The Tremonti’s oxygen abundances are free of these problems and more robust to observational errors since they use many lines.

Figure 4 shows the histograms distributions of the abundance values of the galaxies in the four subgroups, where the median $12+\log(O/H)$ values are 8.77 for vLSBGs, 8.94 for iLSBGs, 9.03 for iHSBGs, 9.06 for vHSBGs (see Table 1). The mean values are 8.77, 8.92, 9.01 and 9.03, respectively. This shows that the vLSBGs have the lowest metallicities among the four subgroups, their $12+\log(O/H)$ abundances are 0.3 dex lower than those of vHSBGs and vHSBGs, and 0.17 dex lower than that of iLSBGs.

However, these results directly show that our vLSBGs and iLSBGs are not as metal-poor as the H II regions in a small sample of LSBGs studied by McGaugh (1994) and

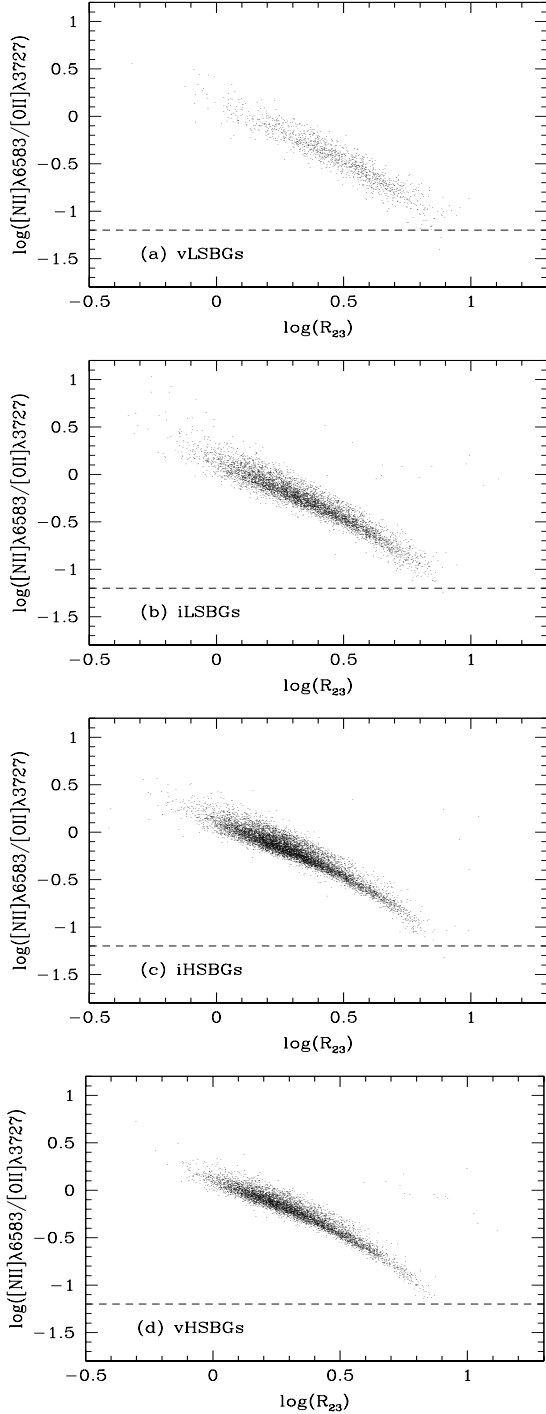


Figure 3. The relationships of $\log([\text{N II}]/[\text{O II}])$ vs. $\log(R_{23})$ for the star-forming sample galaxies in four bins of $\mu_0(B)$: (a) vLSBGs; (b) iLSBGs; (c) iHSBGs; (d) vHSBGs. Most of them have $\log([\text{N II}]/[\text{O II}]) > -1.2$.

some following works, which are 8.06 to 8.20 in median of their $12+\log(\text{O}/\text{H})$. The main reasons for such difference could be the different types of galaxies we studied (most of theirs are dwarfs and ours are much luminous), the different calibrations to derive the oxygen abundances (they used the lower branch R_{23} formula and our oxygen abundances are provided by Tremonti et al. by using the Bayesian

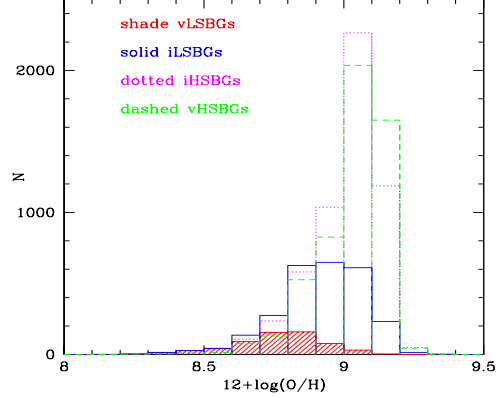


Figure 4. Histogram distributions of $12+\log(\text{O}/\text{H})$ of the star-forming sample galaxies in four bins of $\mu_0(B)$: the median values are 8.77 for vLSBGs, 8.94 for iLSBGs, 9.03 for iHSBGs, 9.06 for vHSBGs.

approach), and the different photoionization models used to estimate oxygen abundances (they used McGaugh 1991 which results in lower oxygen abundances than what used by Tremonti et al.). We will discuss these carefully in Sect.5.2 in details.

3.3 The nitrogen to oxygen ratios

It is possible to estimate the N abundances of galaxies from strong optical emission lines, such as $[\text{N II}]\lambda 6583$, $[\text{O II}]\lambda 3727$ and $\log R_{23}$, which can help to understand the origin of nitrogen.

The basic nuclear mechanism to produce nitrogen is from CNO processing of oxygen and carbon in hydrogen burning. If the “seed” oxygen and carbon are those incorporate into a star at its formation and a constant mass fraction is processed, then the amount of nitrogen produced is proportional to the initial heavy-element abundance, and the nitrogen synthesis is said to be “secondary”. If the oxygen and carbon are produced in the star prior to the CNO cycling (e.g. by helium burning in a core, followed by CNO cycling of this material mixed into a hydrogen-burning shell), then the amount of nitrogen produced may be fairly independent of the initial heavy-element abundance of the star, and the synthesis is said to be “primary” (Vila-Costas & Edmunds 1993). In general, then, primary nitrogen production is independent of metallicity, while secondary production is a linear function of it. The N/O ratio as a function of O/H is the basic method to study the N abundance of galaxies. It could be sensitive to the ratio of intermediate-mass to massive stars since nitrogen mainly come from the intermediate-mass stars and oxygen mostly come from the massive ones.

We use the formula given by Thurston et al. (1996) to estimate the electron temperature in the $[\text{N II}]$ emission region ($t_{\text{NII}} = t_{II}$, in units of 10^4K) from $\log R_{23}$:

$$t_{II} = 6065 + 1600x + 1878x^2 + 2803x^3, \quad (1)$$

where $x = \log(R_{23})$.

Then, $\log(\text{N}/\text{O})$ values are estimated from the $([\text{N II}]\lambda\lambda 6548, 6583)/([\text{O II}]\lambda 3727)$ emission-line ratio and t_{II}

($=t_{\text{NII}}$) by assuming $\frac{\text{N}}{\text{O}} = \frac{\text{N}^+}{\text{O}^+}$, and using the convenient formula based upon a five-level atom calculation given by Pagel et al. (1992) and Thurston et al. (1996):

$$\log\left(\frac{\text{N}^+}{\text{O}^+}\right) = \log\left[\frac{[\text{NII}]6548, 6583}{[\text{OII}]3727, 3729}\right] + 0.307 - 0.02\log t_{\text{H}} - \frac{0.726}{t_{\text{H}}}. \quad (2)$$

We consider that the flux of $[\text{N II}]\lambda 6548$ is equal to one-third of that of the $[\text{N II}]\lambda 6583$ in the calculations.

Figure 5 presents the $\log(\text{N/O})$ vs. $12+\log(\text{O/H})$ relations for our sample galaxies in four bins of $\mu_0(B)$. It shows that the vLSBGs have much less metal-rich and N/O-high objects than the vHSBGs and iLSBGs. iLSBGs also have such less objects than the two subgroups with higher surface brightness. Thus the median values of $\log(\text{N/O})$ are -1.05 for vLSBGs, -0.94 for iLSBGs, -0.85 for iHSBGs and -0.83 for vHSBGs (see Table 1). We also plot the different origin of “primary” (the dot-dashed line), “secondary” (the long-dashed line) component and the combination of these two components (the solid line) taken from Vila-Costas & Edmunds (1993) in this figure. It shows that the $\log(\text{N/O})$ abundances of the sample galaxies are more consistent with the combination of the “primary” and “secondary” components, but the *secondary* component dominates. This result is similar to the previous studies, e.g. Shields et al. (1991), Vila-Costas & Edmunds (1993), Contini et al. (2002), Kennicutt et al. (2003), Liang et al. (2006a), and Mallery et al. (2007). In Fig. 5, the median values of $\log(\text{N/O})$ of the four sub-sample galaxies are also given in each of the 0.1 dex bins of $12+\log(\text{O/H})$ as the big squares.

To present the discrepancies among the median values of the four subgroup galaxies more clearly, we plot their discrepancies in Fig. 6a, where the filled squares are for vLSBGs–vHSBGs, the open squares are for iLSBGs–vHSBGs, and the filled triangles are for iHSBGs–vHSBGs. It shows that such discrepancies are more obvious, up to ~ 0.074 dex, at low metallicity part. The reason could be related to different star formation rate (SFR) in the galaxies there as Molla et al. (2006) suggested. Their Fig. 5 clearly shows that the evolutionary track followed by a given region in the N/O–O/H plane depends strongly on the star formation history of the region: strong bursting star formation histories would produce high oxygen abundances soon and, hence, an early secondary behavior; in contrast, a low and continuous SFR keeps the oxygen abundance low for a long time thus, a large quantity of the primary nitrogen may be ejected reproducing the flat slopes in the N/O–O/H plane. Combined these discussions with our Fig. 5 and Fig. 6a, it suggests that the galaxies with lower surface brightness may have lower SFR, thus their N/O–O/H show more primary nitrogen component at low metallicity region.

In the middle metallicity part, this discrepancy becomes much small, ~ 0.03 dex for vLSBGs–vHSBGs, ~ 0.015 dex for iLSBGs–vHSBGs, and almost no difference between iHSBGs and vHSBGs. However, the discrepancies become obvious (< 0.06 dex) again when the metallicity becomes very high ($12+\log(\text{O/H}) > 9.0$). The reason could be that possibly there are more recently formed massive stars to produce more oxygen elements, which will cause higher O/H but lower N/O since nitrogen mainly comes from the

intermediate-mass stars. These differences in the median-value points suggest that there might be some star formation history (SFH) variation with surface brightness, but to really test this we may need more data at low metallicity region, and also in very high metallicity region. However, we should notice that the theoretical models only predict very large differences in N/O vs. O/H with SFH at metallicities below $12+\log(\text{O/H})=8.0$. Thus, we really want to go to low metallicity to test whether LSBGs and HSBGs have had different SFHs.

These results are consistent with what we found from the stellar population analyses through fitting spectral continua and absorption lines on these sample galaxies as presented in Chen et al. (2010, in preparation), who found that vHSBGs have larger fraction (5%) of young population than vLSBGs. Also Gao et al. (2010) found that the derived ages are 0.2 Gyr younger in HSBGs than in LSBGs generally through fitting the FUV-to-NIR multiwavelength spectral energy distributions (SEDs) of these galaxies by using the PEGASE model (Fioc & Rocca-Volmerange 1997). These results should be not much different from Mattsson et al. (2007), who found that the late-type LSB galaxies did not deviate from the general trend in HSB galaxies and concluded that LSB galaxies probably had the same age as their high surface brightness counterparts, although the global rate of star formation must be considerably lower in these galaxies.

4 RELATIONS AMONG METALLICITY, STELLAR MASS AND SURFACE BRIGHTNESS

We study the relations of $12+\log(\text{O/H})$ vs. stellar mass, $12+\log(\text{O/H})$ vs. $\mu_0(B)$ and stellar mass vs. $\mu_0(B)$ for our sample galaxies in this section. Due to the limits of stellar mass estimates, the available samples in these relations are reduced to be 597 of vLSBGs, 2,609 of iLSBGs, 5,486 of iHSBGs, and 5,291 of vHSBGs.

4.1 Metallicity vs. stellar mass

The stellar mass-metallicity relation (MZR) of galaxies is a fundamental relation to show the evolutionary history and the present properties of galaxies. Generally, the metallicities and stellar masses of galaxies increase with their evolutionary processes. Therefore, usually more massive galaxies are more metal-rich (Tremonti et al. 2004; Liang et al. 2007; Kewley & Ellison 2008 and the references therein). Besides the local galaxies their MZR have been obtained, a sample of galaxies at intermediate redshift ($0.4 < z < 1$) have also been obtained their MZR based on the observed data from large telescope, such as VLT and Keck (Liang et al. 2006b; Rodrigues et al. 2008), even for the galaxies at high redshift ($z \sim 2.3$, Erb et al. 2006).

Fig. 7 presents the MZR for our sample galaxies in four $\mu_0(B)$ bins. The median values of $\log(M_*)$ of the four subgroup galaxies are 9.55, 9.91, 10.21 and 10.29 for vLSBGs, iLSBGs, iHSBGs and vHSBGs, respectively (see Table 1). It shows that the vLSBGs include less samples of metal-rich and massive galaxies than the other three subgroups. The iLSBGs have also less such objects than the iHSBGs and

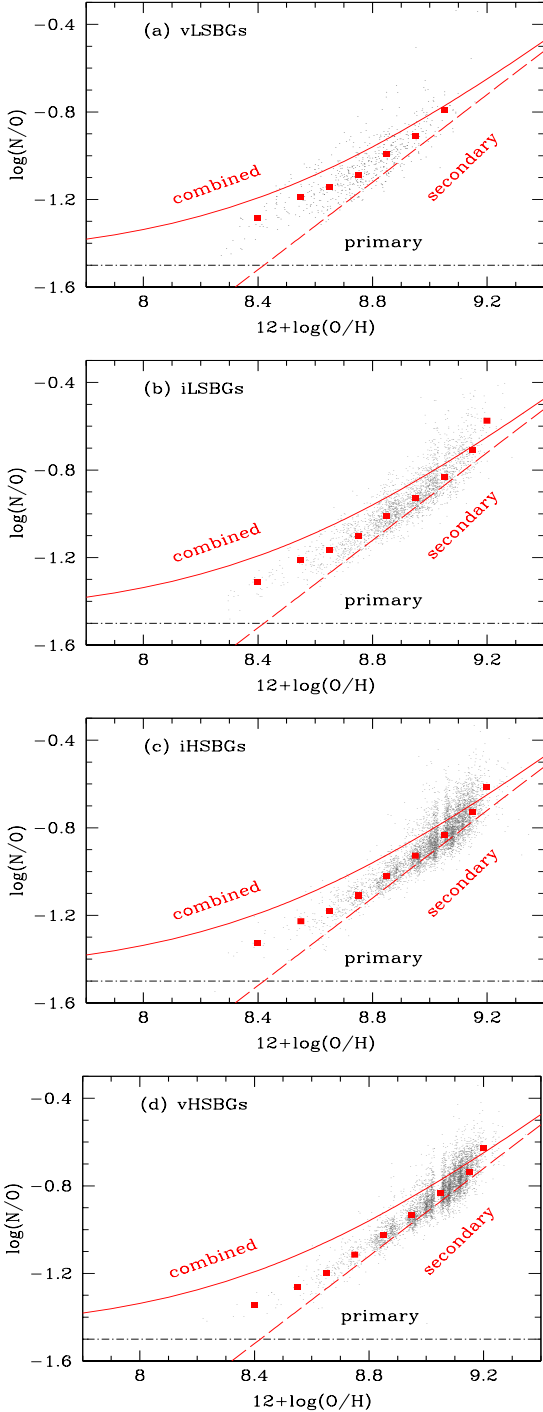


Figure 5. The $\log(N/O)$ abundances of the star-forming sample galaxies in four bins of $\mu_0(B)$: (a) vLSBGs, (b) iLSBGs, (c) iHSBGs, (d) vHSBGs. The “primary” (the dot-dashed line), “secondary” (the long-dashed line) components and the combination of these two components (the solid line) taken from Vila-Costas & Edmunds (1993) have also been plotted. The big squares refer to the median values of $\log(N/O)$ with 0.1 dex bins of $12+\log(O/H)$. (Please see the on-line color version for more details)

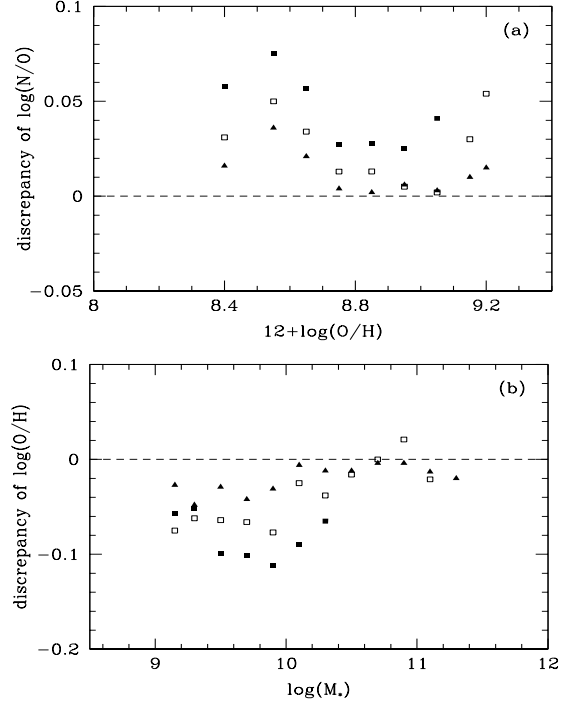


Figure 6. The discrepancies among the median values of the four subgroup galaxies in bins: (a) the median values of $\log(N/O)$ vs. $12+\log(O/H)$ as given in Fig. 5; (b) the median values of $12+\log(O/H)$ vs. stellar mass as given in Fig. 7. The filled squares refer to the difference of vLSBGs–vHSBGs, the open squares refer to the difference of iLSBGs–vHSBGs, and the filled triangles refer to the difference of iHSBGs–vHSBGs.

vHSBGs. Our samples are fall in the regions of the typical SDSS star-forming galaxies (see the dashed line in Fig. 7, and Liang et al. 2007), but with slight difference as discussed below and in Sect. 4.3.

The median values of $12+\log(O/H)$ with 0.2 dex bins of stellar mass are also given as the big squares in Fig. 7 for the four subgroup galaxies. Comparing these median values with the dashed line, HSBGs have slightly higher $12+\log(O/H)$ (~ 0.035 dex) than the normal galaxies at given stellar mass, LSBGs have quite similar metallicities to them except the vLSBGs with larger stellar masses have 0.016-0.039 dex lower $12+\log(O/H)$ than the normal galaxies.

To show more clearly the differences among the median values of the four subgroup galaxies, in Fig. 6b we plot the discrepancies of vLSBGs–vHSBGs as filled squares, the discrepancies of iLSBGs–vHSBGs as open squares, and the discrepancies of iHSBGs–vHSBGs as filled triangles. It shows that vHSBGs have higher $12+\log(O/H)$ abundances than vLSBGs for lower mass galaxies, 0.06-0.11 dex up to $\log(M_*) \sim 10.3$ with the peak around $\log(M_*) \sim 9.9$. The corresponding overabundances are 0.06-0.08 dex for iLSBGs, and ~ 0.04 dex for iHSBGs. In more massive region, there is no much difference for their metallicities among iLSBGs, iHSBGs and vHSBGs. These results show that the MZR of galaxies have some differences following their surface brightness.

In these $12+\log(O/H)$ vs. $\log(M_*)$ relations of the four subgroup galaxies, we also calculate the scatter of the data comparing with the median values in mass bins. The results

are about 0.12 for vLSBGs, 0.09 for iLSBGs, 0.08 for both iHSBGs and vHSBGs.

4.2 Central surface brightness vs. metallicity

Figure 8a shows the relations of $12+\log(\text{O}/\text{H})$ vs. $\mu_0(B)$ for our sample galaxies in four subgroups. The median values in each of the bins of 0.2 in $\mu_0(B)$ are also given (the big squares), as well as the three vertical long-dashed lines at $\mu_0(B)=21.25, 22.0$ and 22.75 mag arcsec $^{-2}$ to mark the ranges of $\mu_0(B)$ for the four subgroups. A general varying trend shows that, for the vLSBGs and iLSBGs, the galaxies with lower surface brightness values have lower metallicities. The iHSBGs also following this trend slightly. The vHSBGs do not show such trend.

McGaugh (1994) did not find direct correlation between metallicities and surface brightnesses for their small sample. Since our sample is much larger, our results could be the first time to show such correlation between $12+\log(\text{O}/\text{H})$ and $\mu_0(B)$ for LSBGs although the scatter is obvious. However, Bell & de Jong (2000) has investigated the relation between the average metallicities inferred from the colors of each galaxy annulus and the average K-band surface brightness in that annulus (their Fig.7b). They found strong, statistically significant correlations between local metallicity and the K-band surface brightness. The LSBGs with lower surface brightness may have less star forming and/or evolve more slowly than those with higher surface brightness.

In these $12+\log(\text{O}/\text{H})$ vs. $\mu_0(B)$ relations, the scatter of the data comparing with the median values in $\mu_0(B)$ bins are about 0.15 for both vLSBGs and iLSBGs, 0.13 for iHSBGs, and 0.12 for vHSBGs. These scatters are larger than those in the $12+\log(\text{O}/\text{H})$ vs. $\log(M_*)$ relations.

4.3 Central surface brightness vs. stellar mass

We further obtain the relations of $\mu_0(B)$ vs. stellar masses for our sample galaxies, which are given in Fig. 8b. Here the scatter is larger than in Fig. 8a. Similarly, it shows that, for the vLSBGs and iLSBGs, the galaxies with lower surface brightness have smaller stellar mass generally. The iHSBGs also follow this trend, but the vHSBGs do not. Combining this relation with the relation of $\mu_0(B)$ vs. $12+\log(\text{O}/\text{H})$, these are consistent with the correlation between stellar masses and metallicities of the sample galaxies.

However, the trend of $12+\log(\text{O}/\text{H})$ following surface brightness for the vLSBGs and iLSBGs as shown in Fig. 8a could be linked with stellar masses. Therefore, in Fig. 8c we plot the residuals of the measured $12+\log(\text{O}/\text{H})$ and the calculated ones using the calibration formula from stellar mass derived by Liang et al. (2007) from the SDSS-DR4 star-forming galaxies, i.e., the dashed line in our Fig. 7.

The big squares in Fig. 8c show the median values of the metallicity residuals following surface brightness with bins of 0.2. Comparing with vHSBGs, they show about 0.035 dex higher $12+\log(\text{O}/\text{H})$ for iHSBGs, quite similar metallicity for iLSBGs and about 0.027 dex (0.016 to 0.039 dex following decreasing surface brightness) lower $12+\log(\text{O}/\text{H})$ for vLSBGs. These discrepancies following surface brightness may be important, though not the only thing, for the scatters of the data in relations of $12+\log(\text{O}/\text{H})$ vs. stellar mass and $12+\log(\text{O}/\text{H})$ vs. surface brightness.

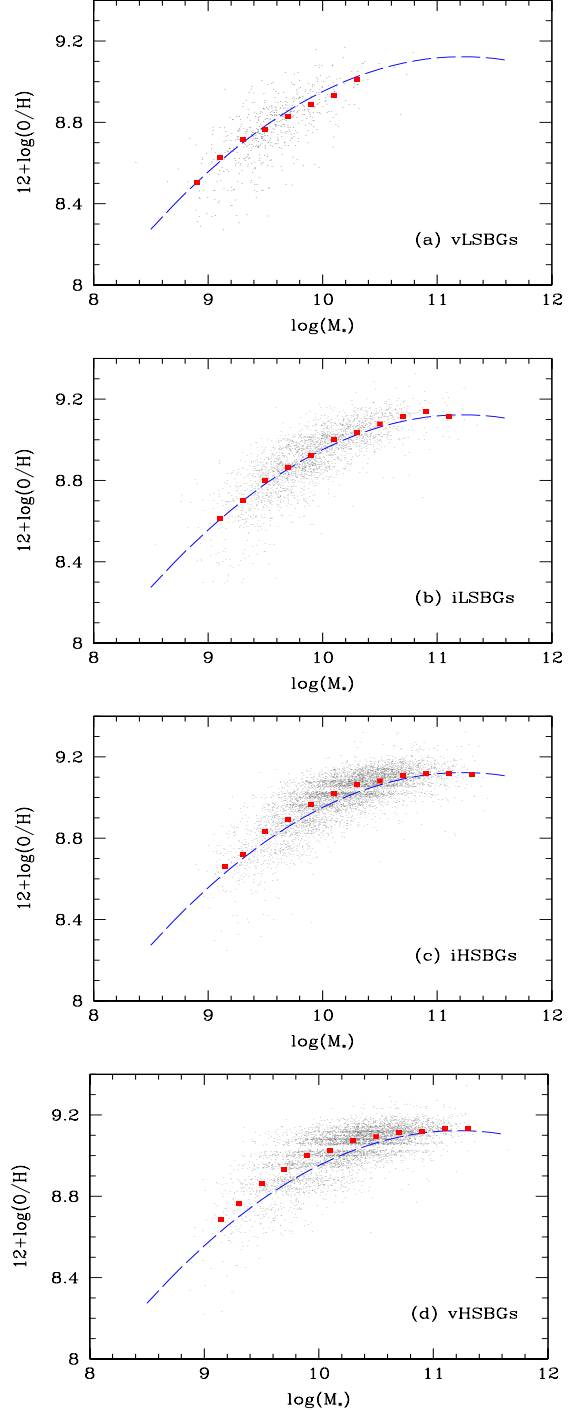


Figure 7. The relations of stellar mass and $12+\log(\text{O}/\text{H})$ for the star-forming sample galaxies in four bins of $\mu_0(B)$: (a) vLSBGs, (b) iLSBGs, (c) iHSBGs, (d) vHSBGs. The line is taken from Liang et al. (2007) for the SDSS-DR4 star-forming galaxies. The big squares refer to the median values of $12+\log(\text{O}/\text{H})$ with 0.2 dex bins of $\log(M_*)$. (Please see the on-line color version for more details)

Moreover, these results are just consistent well with those shown in Fig. 7 (comparing the median-value points with the dashed line). These very small residuals are lower than what found by Tremonti et al. (2004, their Fig.7) with stellar surface density and Ellison et al. (2008, their Fig.2) with dividing by r-band half light radius. The reason could be also related to our sample galaxies having very small fracDev_r and being nearly face-on. It might also be the case that a galaxy's metallicity is more closely linked with its surface mass density than its B-band surface brightness. $\mu_0(B)$ is likely very sensitive to any very recent perturbation in the SFH whereas metallicity will be more closely related to the time-integrated SFH. In addition, this weak dependence can also explain the relations of dust extinction A_V with surface brightness as shown in Fig. 2, which is consistent with the Fig.12 in Liang et al. (2007) about the relations of A_V following $\log M_*$ for the star-forming galaxies. Then the 0.3dex difference in oxygen abundances between vLSBGs and vHSBGs (Fig. 4) could be also understood well.

5 DISCUSSIONS

5.1 The Aperture effects

Here we discuss the fiber aperture effects on metallicity estimates for our sample galaxies. Tremonti et al. (2004) has discussed the weak effect of the 3'' aperture of the SDSS spectroscopy on estimated metallicities of the sample galaxies with redshifts $0.03 < z < 0.25$. We have used redshift $0.04 < z < 0.25$ as one of the sample selection criteria by following Kewley et al. (2005), who recommended that, to get reliable metallicities, redshifts $z > 0.04$ are required for the SDSS galaxies to ensure a covering fraction $>20\%$ of the galaxy light.

To check how much the light of the galaxy was covered by the fiber observation, one simple and accurate way is to compare the “fiber” and “petrosian” magnitudes of the SDSS galaxies. The fiber mag is a measurement of the light going down the fiber and the petrosian mag is a good estimate of the total magnitude. Thus, we adopt the formula below to estimate how much light was covered by the fiber observations:

$$\text{light_fraction} = 10^{(-0.4 * (\text{fiber_mag} - \text{petro_mag})_r)}. \quad (3)$$

Fig. 9 shows the calculated light fractions for the four sub-samples. It shows that, the light fractions of vLSBGs (597), iLSBGs (2,609), iHSBGs (5,486) and vHSBGs (5,291) are about 0.12, 0.15, 0.21 and 0.30 (in median), respectively. Although the light fractions of vLSBGs and iLSBGs are lower than 0.2 which was suggested by Kewley et al. (2005), we believe that this is not a serious problem for estimating the metallicities of the sample galaxies since LSBGs may have no strong radial oxygen abundance gradients, which has been found by de Blok & van der Hulst (1998).

To further check whether the presence of a stellar bulge affects the relationships among stellar mass, metallicity and surface brightness of galaxies or not, we only select those samples having $\text{fracDev}_r \sim 0$, which means that the galaxy could be purely disk one. Then we re-plot Fig. 8 and find they show very similar distributions to the previous plots. Thus, we believe that the bulge light won't affect much

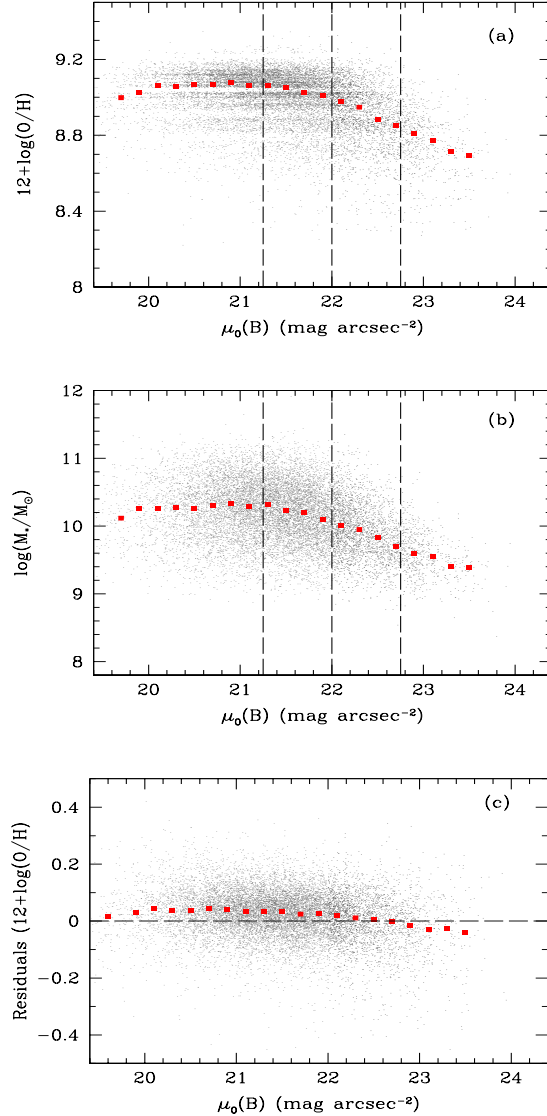


Figure 8. The relations among $12+\log(\text{O}/\text{H})$, stellar masses and $\mu_0(B)$ for the star-forming sample galaxies: (a) $12+\log(\text{O}/\text{H})$ vs. $\mu_0(B)$, (b) stellar mass vs. $\mu_0(B)$, (c) the residuals between the measured $12+\log(\text{O}/\text{H})$ and the ones calculated from the calibration with stellar mass (the dashed line in Fig. 7, taken from Liang et al. 2007), which is to remove the stellar mass effects. The median values in each of the bins of 0.2 in $\mu_0(B)$ are also given as the big squares, and the three vertical long-dashed lines at 22.75, 22.0 and 21.25 mark the ranges of $\mu_0(B)$ for the four subgroups of vLSBGs, iLSBGs, iHSBGs and vHSBGs.

these corresponding relationships for the sample galaxies. This is consistent with what have been found by Ellison et al. (2008) and Tremonti et al. (2004). Ellison et al. (2008) showed that Bulge-to-total ratio has almost no impact on the mass-metallicity relation (their Fig 3) and Tremonti et al. (2004) showed that Concentration is also not important (their Fig. 7). But we should still keep in mind that generally the central regions have higher stellar surface density (independently of the presence of a bulge) than outer regions, and more metal rich.

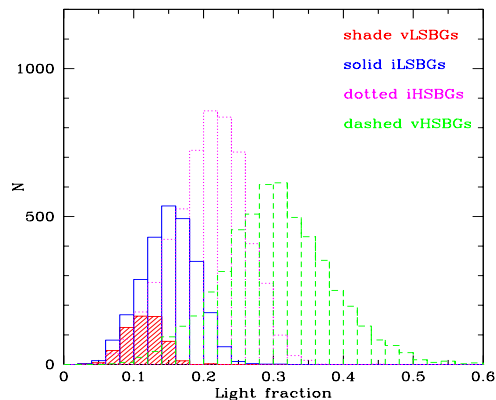


Figure 9. The histogram distributions of the light fraction (Eq. (3)) with bins of 0.01 for the sample galaxies in four subgroups. The median values of the light fractions in four bins of $\mu_0(B)$ are 0.12 for vLSBGs, 0.15 for iLSBGs, 0.21 for iHSBGs, 0.30 for vHSBGs.

5.2 Comparisons with previous studies on metallicities of LSBGs

We find that our large sample of LSB disc galaxies selected from the SDSS have no that low metallicities as the H II regions in a small sample of LSBGs studied in literature. The median $12+\log(O/H)$ of our vLSBGs (with $\mu_0(B) > 22.75$ mag arcsec $^{-2}$), is 8.77, and the median $12+\log(O/H)$ of the iLSBGs (with $\mu_0(B)=22.75-22.0$ mag arcsec $^{-2}$) is 8.94. However, some researches have been obtained much lower oxygen abundances for the H II regions in a small sample of LSBGs, i.e., 8.06 to 8.20 of $12+\log(O/H)$ (in median in their samples) in McGaugh (1994), Roennback & Bergvall (1995), de Blok & van der Hulst (1998) and Kuzio de Naray et al. (2004). How to understand this discrepancy?

The most possible reason could be our sample galaxies are more luminous than theirs indeed. We have selected the sample with $M_B < -18$ mag which exclude some dwarf galaxies from the normal star-forming disc galaxies. Most of our sample galaxies are luminous with $M_B < -19$ mag. Another reason could be that they (mostly) adopted the R_{23} calibration of lower branch, which surely result in low oxygen abundances, while our oxygen abundances are those obtained by the MPA/JHU group as Tremonti et al. (2004) by using the Bayesian approach. Moreover, the different photoionization models used to estimate oxygen abundances could also cause some differences. They used McGaugh (1991) which results in ~ 0.1 dex lower oxygen abundances than what used by Tremonti et al. (2004). In addition, the metallicities from literature come from H II regions which are often observed at large radii in the galaxy, whereas our measurements come from the central few kpc. If there are metallicity gradients in the galaxies then this will cause the SDSS metallicities to be a bit higher.

In McGaugh (1994), 41 H II regions in 22 LSBGs were obtained their O/H abundances, which are about $12+\log(O/H) \sim 8.06$ (in median). The sample was selected from the lists of Schombert & Bothun (1988) and Schombert et al. (1992), and from the UGC. All these galaxies have central surface brightness well below the Freeman (1970) value of $\mu_0 = 21.65$ mag arcsec $^{-2}$, with the sample median be-

ing 23.4 mag arcsec $^{-2}$. Their Fig.10 shows that almost half of their samples are faint having $M_B > -18$ mag, which should belong to the dwarfs, and another half objects mostly have $-20 < M_B < -19$ mag (the cosmological parameter H_0 has been corrected from 100 to 70 km s $^{-1}$ Mpc $^{-1}$). Even these brighter galaxies are comparable with part of our sample galaxies in luminosity, McGaugh (1994) used the lower branch formula of R_{23} for metallicity estimates, thus the oxygen abundances of their samples are still lower than ours as discussed below.

Another key point is which calibration (the lower branch or upper branch one) are used to estimate the oxygen abundances of the galaxies. McGaugh (1994) used $\log([N II]/[O II]) < -1.0$ to judge that their samples belong to the lower branch of metallicity, and then used the lower branch R_{23} formula (McGaugh 1991) to calculate the oxygen abundances of their H II regions. Indeed their Fig.3 shows that some (almost half) of their samples have $\log([N II]/[O II])$ between -1.0 and -1.2 . The latter value, -1.2 , is a recent recommendation (Kewley & Ellison 2008) and is adopted here by us to separate the upper and lower branches of metallicities.

To be sure the calibration method is another main reason (may be the most important one) for the difference between the abundances of McGaugh (1994) and ours, we select those of our sample galaxies having $-1.2 < \log([N II]/[O II]) < -1.0$ and re-calculate their oxygen abundances by using the same method as McGaugh (1994), i.e., the lower branch R_{23} formula from McGaugh (1991). The corresponding analysis formula from Kobulnicky et al. (1999) is used here. Then Fig. 10 explains the differences quite well. It shows that the $12+\log(O/H)$ of all these sample galaxies will become much lower, 0.2 dex-0.6 dex lower, than the original ones. And now they are consistent with the estimates of McGaugh (1994).

In addition, de Blok & van der Hulst (1998) present measurements of the oxygen abundances of 64 H II regions in 12 LSBGs, and found their oxygen abundances are low, in a range of $12+\log(O/H) \sim 7.83$ to 8.84, and the median value is 8.20. They confirm the results of McGaugh (1994) that LSBGs are metal-poor. However, most of their sample galaxies are the same ones as in McGaugh (1994). Also almost half of their samples have $-1.2 < \log([N II]/[O II]) < -1.0$, but they use the lower branch R_{23} formula for them. Kuzio de Naray et al. (2004) combined their new abundance measurements with data from McGaugh (1994) and de Blok & van der Hulst (1998) to produce average abundances for 18 galaxies. They found that their galaxies to be significantly offset from the Tremonti's luminosity-metallicity and stellar mass-metallicity relations. The 0.3 dex spread of the various local luminosity-metallicity relations in their Fig.11 highlights the discrepancies that can arise from different sample selections (theirs are fainter than ours) and metallicity calibrations (they use the lower branch R_{23} calibration). They also use the $\log([N II]/[O II]) = -1$ as cut for the upper and lower branches and that the majority of their data was from McGaugh (1994).

Roennback & Bergvall (1995) obtained spectroscopic observations of 16 blue LSBGs. These are among the bluest and dimmest objects found in the ESO-Uppsala Catalogue. Oxygen abundances are derived in 24 H II regions. They are at the lower boundary found for galaxies with

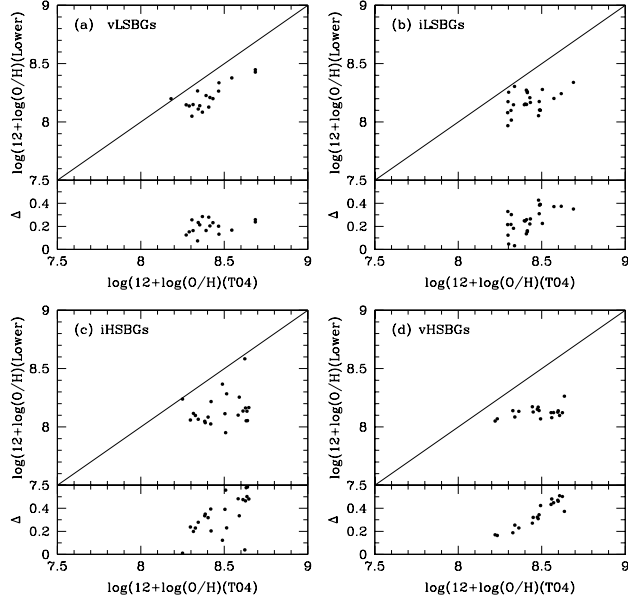


Figure 10. Comparing the $12+\log(\text{O}/\text{H})$ abundances estimated from lower branch formula of R_{23} (McGaugh 1991; Kobulnicky et al. 1999) and the abundances from Tremonti et al. (2004) for the sample galaxies having $-1.2 < \log([\text{N II}]/[\text{O II}]) < -1.0$: (a) vLSBGs, (b) iLSBGs, (c) iHSBGs, (d) vHSBGs. The top panels show the direct comparisons, and the lower panels show the residuals.

$12+\log(\text{O}/\text{H}) \sim 7.54-8.09$. These bluest, dimmest and metal-poor objects are not the same as our normal disk galaxies from SDSS.

As the discussions above, we now can understand the discrepancies between the metallicity estimates of our LSBGs and those of the H II regions in LSBGs in literature. It could be due to the different types of galaxies intrinsically, and the different oxygen abundance calibration methods and different photoionization models used.

Another point we would like to address is that our sample galaxies selected by emission lines (see Sect.2) may exclude the ones without much star formation, which often be as LSBGs. Indeed, in all our 12,282 LSBGs (Zhong et al. 2008), there are 2,817 classified as vLSBGs, and the rest 9,465 are iLSBGs. Further with the $0.04 < z < 0.25$ cut, there are 2,355 vLSBGs and 8,731 iLSBGs selected. Among them, 2,305 and 8,637 are measured their equivalent weights of $\text{H}\alpha$ emission lines, $\text{EW}(\text{H}\alpha)$, respectively. Then the selected 1,364 emission-line vLSBGs (see Sect.2) correspond to about 59% of those selected from photometry plus redshift cut plus $\text{EW}(\text{H}\alpha)$. For iLSBGs, this fraction is about 70% ($=6,055/8,637$). Fig. 11 shows the histogram distributions of $\text{EW}(\text{H}\alpha)$ for vLSBGs (left panel) and iLSBGs (right panel). Namely, the solid lines are for the 2,305 and 8,637 sample galaxies before applying emission-line criterion, and the dashed lines are for the 1,364 and 6,055 galaxies of vLSBGs and iLSBGs with emission-line criterion (criterion (v) in Sect.2). They do show that most of the rejected LSBGs by emission-line cut have lower $\text{EW}(\text{H}\alpha)$ values.

Thus we should keep in mind that those galaxies without obvious emission lines could have very few star formation and then few metal enrichment, and could have lower metal abundances then. We should also notice that a very

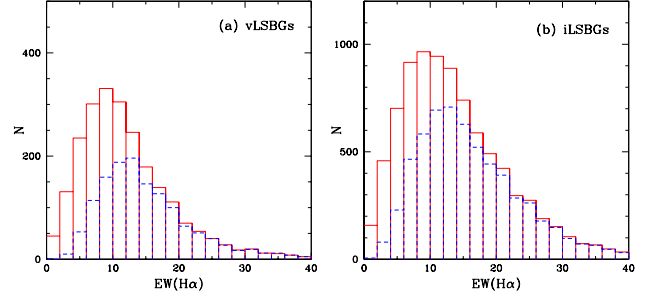


Figure 11. Histogram distributions of $\text{EW}(\text{H}\alpha)$ to compare the selected emission-line LSBGs following criteria (i-v) in Sect.2 with those sample before considering emission-line cut (with criteria (i-iv) in Sect.2). (a) for vLSBGs and (b) for iLSBGs. The solid lines show the distribution of the sample selected before considering emission-line cut (2,305 and 8,637), and the dashed lines refer to those have been considered emission-line cut (1,364 and 6,055 for vLSBGs and iLSBGs, respectively).

important point is that the previous studies target H II regions at any position in the galaxy whereas SDSS is just sensitive to star formation in the nuclear region. Thus, the previous works are probably include galaxies with very low SFR and just a few H II regions that get rejected from the SDSS sample.

6 SUMMARY AND CONCLUSIONS

In this second paper of our series work about a large sample of LSBGs ($\mu_0(B) > 22$ mag arcsec $^{-2}$) selected from the SDSS-DR4 main galaxy sample (Zhong et al. 2008, the Paper I), which are low-inclination, disk-dominated galaxies, we study the spectroscopic properties of the star-forming sample galaxies including dust extinction, strong emission-line ratios, oxygen abundances, $\log(\text{N}/\text{O})$ abundance ratios, and the relations of $12+\log(\text{O}/\text{H})$ vs. stellar mass, $12+\log(\text{O}/\text{H})$ vs. $\mu_0(B)$, and stellar mass vs. $\mu_0(B)$. For comparison, a large sample of HSBGs ($\mu_0(B) < 22$ mag arcsec $^{-2}$) is also selected simultaneously and done similar analyses. To be in more details, the entire sample galaxies of LSBGs and HSBGs are further divided into four subgroups according to their $\mu_0(B)$ (in units of mag arcsec $^{-2}$): i.e., vLSBGs with 24.5-22.75, iLSBGs with 22.75-22.0, iHSBGs with 22.0-21.25, and vHSBGs with < 21.25 . Their resulted properties are summarized as follows.

(i) The AGN fractions of the sample galaxies are small, less than 9%, verified by the BPT diagrams from emission-line ratios. The reason could be that our fracDev_r cut has selected against galaxies with bulges. We select the star-forming galaxies for further studies.

(ii) LSBGs span a wide range in dust attenuation, metallicity, N/O and stellar mass. The median values of these property parameters all increase with surface brightness as can be seen in Table 1. However, these trends can, for the most part be accounted for by the differences in stellar mass among the samples. Most of our sample galaxies have $\log([\text{N II}]/[\text{O II}]) > -1.2$, which means they belong to the upper branch of R_{23} vs. metallicity relation. Thus our vLSBGs and iLSBGs are not as metal-poor as the H II regions in a small sample of LSBGs studied by McGaugh (1994)

and some following works (8.06-8.20 of $12+\log(\text{O}/\text{H})$ in median). One reason of this discrepancy could be that our sample galaxies are more luminous than theirs intrinsically. The second reason could be the different calibrations of R_{23} for metallicity, previous studies, such as McGaugh et al. (1994), adopted $\log([\text{N II}]/[\text{O II}]) > -1.0$ (higher than -1.2 , what we used) to judge and found most of their samples were in the lower branch of R_{23} vs. metallicity relation, while we adopt the oxygen abundances of the galaxies obtained by using the Bayesian approach by the MPA/JHU group as Tremonti et al. (2004). This could be well explained by Fig. 10 for those our sample galaxies having $-1.2 < \log([\text{N II}]/[\text{O II}]) < -1.0$.

(iii) The $\log(\text{N}/\text{O})$ abundances of our sample galaxies are more consistent with the combination of the “primary” and “secondary” components, but the “secondary” component dominates. In the $\log(\text{N}/\text{O})$ vs. $12+\log(\text{O}/\text{H})$ relations of the four subgroup galaxies, the median values of them at given O/H show slight differences (< 0.074 dex) following surface brightness as shown in Fig. 5 and Fig. 6a. These may mean that the sample galaxies may have some but not quite much difference in star formation history, stellar populations, and enrichment history of chemical elements, such as nitrogen and oxygen, as well as the ratio of intermediate-mass to massive stars.

(iv) The relations between stellar masses and $12+\log(\text{O}/\text{H})$ for our sample galaxies show that the vLSBGs have less metal-rich and massive ones than other three subgroups. And the iLSBGs have also less such objects than the iHSBGs and vHSBGs. We would like to highlight that the LSBGs in our sample span a wide range of stellar mass and metallicity although having less massive and metal-rich ones; LSBGs are not much more metal poor than HSBGs of the same mass (less than 0.11 dex shown by the median-value points in Fig. 6b).

(v) For the vLSBGs and iLSBGs, the galaxies with lower surface brightnesses have lower metallicities, and have smaller stellar masses generally. The iHSBGs also follow this trend slightly, but the vHSBGs do not. These trends could be intrinsically linked to stellar masses. If the effects of stellar masses are removed by calculating the residuals between the measured oxygen abundances and those calculated from stellar masses using formula, then the four subgroups do not show much difference (from $+0.035$ to -0.039 dex as given in Fig. 8c). In a word, the metallicity of LSBGs is correlated with $\mu_0(B)$, but more tightly correlated with stellar mass; the apparent correlation of $\mu_0(B)$ and O/H is a consequence of the correlation with stellar mass; the residuals of the MZR show very slightly correlation with $\mu_0(B)$, which means that these LSBGs and HSBGs may have some variation but not quite much in star formation history and chemical enrichment history.

ACKNOWLEDGMENTS

We appreciate our referee, who provide very admirable, constructive and helpful comments and suggestions, which help to improve well our work. We would like to thank Prof. Rob Kennicutt and Myriam Rodrigues for helpful and interesting discussions during the IAU Symposium 262 in Rio de Janeiro in August 2009. We thank Dr. Shiyin Shen and Dr. Ruixiang Chang for useful discussions. This work was supported

by the Natural Science Foundation of China (NSFC) Foundation under Nos.10933001, 10973006, 10973015, 10673002; and the National Basic Research Program of China (973 Program) Nos.2007CB815404, 2007CB815406, and No. 2006AA01A120 (863 project). We thank the SDSS and the MPA/JHU group to make the database and many measurements of the SDSS galaxies be available for public use.

REFERENCES

- Adelman-McCarthy J. et al. 2006, ApJS, 162, 38
- Baldwin J. A., Phillips M. M. & Terlevich R. 1981, PASP, 93, 5
- Bell E. F. & de Jong R. S., 2000, MNRAS, 312, 497
- Bergvall N., Zackrisson E., Caldwell B., 2009, arXiv 0909.4296
- Bothun G. D., Impey C., & McGaugh S., 1997, PASP, 109, 745
- Brinchmann J., Charlot S., White S. D. M., Tremonti C., Kauffmann G., Heckman T., Brinkmann J., 2004, MNRAS, 351, 1151
- Bruzual A.G., Charlot S., 2003, MNRAS, 344, 1000
- Caldwell B. & Bergvall N., 2007, Proceedings of the IAU Symposium 235, p.82
- Chang R. X., Shen S. Y., Hou J. L., Shu C. G., Shao Z. Y., 2006, MNRAS, 372, 199
- Contini T., Treyer M. A., Sullivan M., Ellis R. S., 2002, MNRAS, 330, 75
- de Blok W. J. G. & van der Hulst J. M., 1998, A&A, 335, 421
- de Blok W. J. G., van der Hulst J. M., Bothun G. D., 1995, MNRAS, 274, 235
- Disney M. J., 1976, Nature, 263, 573
- Erb D. K., Shapley A. E., Pettini M., Steidel C. C., 2006, ApJ, 644, 813
- Fioc M. & Rocca-Volmerange B., 1997, A&A, 326, 950
- Freeman K. C., 1970, ApJ, 160, 811
- Gallazzi A., Charlot S., Brinchmann J., White S. D. M., Tremonti C., 2005, MNRAS, 362, 41
- Gao D., Liang Y. C., Liu S. F. et al. 2010, RAA (submitted)
- Graham A. W. & Worley C. C., 2008, MNRAS, 388, 1708
- Impey C. D. & Bothun G. D., 1997, ARA&A, 35, 267
- Impey C. D., Burkholder V., Sprayberry D., 2001, AJ, 122, 2341
- Impey C. D., Sprayberry D., Irwin M. J., Bothun G. D., 1996, AJ, 105, 209
- Kauffmann G., Heckman, T. M., Tremonti, C. et al. 2003a, MNRAS, 346, 1055
- Kauffmann G., Heckman, T. M., White, S. D. M. et al., 2003b, MNRAS, 341, 33
- Kennicutt R. C. Jr., Bresolin F., Garnett D. R., 2003, ApJ, 591, 801
- Kewley L. J. & Dopita M. A. 2002, ApJS, 142, 35
- Kewley L. J., Dopita M. A., Sutherland R. S., Heisler C. A., Tervena J. 2001, ApJ, 556, 121
- Kewley L. J. & Ellison S. L., 2008, ApJ, 681, 1183
- Kewley L. J., Jansen R. A., Geller M. J., 2005, PASP, 117, 227
- Kniazev A. Y., Grebel E. K., Pustilnik S. A., Pramskij A. G., Kniazeva T. F., Prada F., Harbeck D., 2004, AJ, 127, 704

- Kobulnicky H.A., Kennicutt R.C.Jr., Pizagno J.L., 1999, *ApJ*, 514, 544
- Kormendy J., Richstone D., 1995, *ARA&A*, 33, 581
- Kuzio de Naray, R., McGaugh, S. S., de Blok, W. J. G., 2004, *MNRAS*, 355, 887
- Liang, Y. C., Hammer, F., Flores, H., Elbaz, D., Marcillac, D., Cesarsky, C. J., 2004, *A&A*, 423, 867
- Liang, Y. C., Hammer, F., Flores, H., 2006b, *A&A*, 447, 113
- Liang, Y. C., Hammer, F., Yin, S. Y. et al. 2007, *A&A*, 474, 807
- Liang, Y. C., Yin, S. Y., Hammer, F., Deng, L. C., Flores, H., Zhang, B., 2006a, *ApJ*, 652, 257
- Magorrian J., Tremaine S., Richstone D. et al. 1998, *AJ*, 115, 2285
- Mallery, R. P., Kewley, L., Rich, R. M., Salim, S., Charlot, S., Tremonti, C., 2007, *ApJS*, 173, 482
- Mattsson L., Caldwell B., Bergvall N., 2008, *ASPC*, 396, 155 (arXiv:0712.0345)
- McGaugh, S. S. 1991, *ApJ*, 380, 140
- McGaugh, S. S., 1994, *ApJ*, 426, 135
- McGaugh, S. S., 1996, *MNRAS*, 280, 337
- Molla M., Vilchez J. M., Gavilan M., Diaz A. I., 2006, *MNRAS*, 372, 1069
- Monnier-Ragaigne D., van Driel W., Schneider S., Jarrett T., Balkowski C., 2003a, *A&A*, 405, 99
- Monnier-Ragaigne D., van Driel W., O'Neil K., Schneider S. E., Balkowski C., Jarrett T. H., 2003b, *A&A*, 408, 67
- Monnier Ragaigne D., van Driel W., Schneider S. E., Balkowski C., Jarrett T. H., 2003c, *A&A*, 408, 465
- Nagao T., Maiolino R., Marconi A. 2006, *A&A*, 459, 85
- O'Neil K., Bothun G. D., Cornell M., 1997a, *AJ*, 113, 1212
- O'Neil K., Bothun G. D., Schombert J., Cornell M. E., Impey C. D., 1997b, *AJ*, 114, 2448
- Osterbrock D. E. 1989, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*. Mill Valley, California: University Science Books
- Pagel B.E.J., Simonson E. A., Terlevich R. J., Edmunds M. G. 1992, *MNRAS*, 255, 325
- Rodrigues M., Hammer F., Flores H., Puech M., Liang Y. C. et al. 2008, *A&A*, 492, 371
- Roennback J. & Bergvall N., 1995, *A&A*, 302, 353
- Rosenbaum S. D. & Bomans D. J., 2004, *A&A*, 422, L5
- Rosenbaum S. D., Krusch E., Bomans D. J., Dettmar R.-J., 2009, *A&A*, 504, 807
- Schombert J. M. & Bothun, G. D., 1988, *AJ*, 95, 1389
- Schombert J. M., Bothun G. D., Schneider S. E., McGaugh S. S., 1992, *AJ*, 103, 1107
- Seaton M. J. 1979, *MNRAS* 187, 73
- Shields G. A., Skillman E. D., Kennicutt R. C. Jr, 1991, *ApJ*, 371, 82
- Stoughton C. et al. 2002, *AJ*, 123, 485
- Strateva I., Ivezić Z., Knapp G. R. et al. 2001, *AJ*, 122, 1861
- Strauss M. A. et al. 2002, *AJ*, 124, 1810
- Thurston T. R., Edmunds M. G., Henry R. B. C. 1996, *MNRAS*, 283, 990
- Tremonti C. A., Heckman T. M., Kauffmann G. et al. 2004, *ApJ*, 613, 898
- van der Hulst J. M., Skillman E. D., Smith, T. R., Bothun, C. D., McGaugh, S. S., de Blok W. J. G., 1993, *AJ*, 106, 548
- Veilleux S. & Osterbrock D. E. 1987, *APJS*, 63, 295
- Vila-Costas M. B. & Edmunds M. G. 1993, *MNRAS*, 265, 119
- York D. G. et al. 2000, *AJ*, 120, 1579
- Zaritsky D., Kennicutt R. C., Huchra J. P., 1994, *ApJ*, 420, 87
- Zhong G., Liang Y. C., Liu F. S. et al. 2008, *MNRAS*, 391, 986 (Paper I)
- Zwicky F., 1957, in *Morphological Astronomy* (New York, Springer-Verlag)